Flow Regime Of The Missouri River Below Gavins Point Dam

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Introduction

Revised discharge frequency relationships were developed for the Missouri River below Gavins Point Dam. Daily flow hydrographs were developed for both natural and regulated flow conditions over a 100-year period by means of model studies, developing a homogenous record for both flow conditions. Natural (or unregulated) flows were estimated by adjusting the observed flow record to reflect water resource development impacts such as irrigation depletions, reservoir regulation and evaporation, and other consumptive water uses. Mean annual, monthly and daily flows were derived from the flow record, as well as peak annual flows. Results of the study show significant differences in the natural flow regime over several periods of time. Results also show differences in the natural flow hydrograph along the river due to watershed and climatic effects. Period of record regulated flow hydrographs were estimated by adjusting all water resource development in the basin to current levels of development. A relationship was determined between the unregulated and regulated annual peaks and used to develop a discharge-frequency relationship at each gage location. The application of flow-frequency results to address environmental issues including the evaluation of endangered species flow regime for current and historical flow is discussed.

Previous Studies. Several studies have been undertaken in the past to define the flow frequency relationship of the Missouri River for various purposes pertaining to flood control measures. Past studies include the 308 Report (U.S. Secretary of War), the Flood Control Act of 1944 (U.S. Congress, 1944), Missouri River Levees, Definite Project Report (USACE, 1946), the Main Stem Flood Control Benefits Re-evaluation (USACE, 1956), and the Missouri River Agricultural Levee Restudy Program (USACE, 1962). Hydrologic data developed as part of the 1962 study included flow hydrographs, annual peak discharge probability curves, stage-discharge rating curves, evaluation of levee confinement effects, and effects of reservoir control. The discharge frequency relationships derived from this study are shown in Table 1.

Table 1. 1962 Missouri River Discharge-Frequency

LOCATION	50 %	10 %	2%	1%
Sioux City	44,000	65,000	82,000	90,000
Omaha	74,000	125,000	170,000	190,000
Nebraska City	108,000	160,000	200,000	220,000
Rulo	117,000	170,000	220,000	241,000

Basin Description. The Missouri River rises along the Continental Divide in the northern Rocky Mountains and flows generally easterly and southeasterly to join the Mississippi River near St. Louis Missouri. The river drains nearly 530,000 square miles in Canada and 10 states, or an area equal to one-sixth of the contiguous United States. Its headwaters begin near Three Forks, Montana where the Madison River, the Jefferson River and the Gallatin River join to form the Missouri River. From there it travels 2,315 square miles to its confluence, making it the longest river in the United States. Major Missouri River tributaries are the Yellowstone River, which drains an area of 70,000 square miles, the Platte River with a 90,000 square mile drainage area; and the Kansas River, which drains an area of approximately 60,000 square miles

Average annual precipitation varies from over 40 inches in parts of the Rocky Mountains and southeastern parts of the basin, to less than 10 inches immediately east of the Rocky Mountains. Temperature extremes range from winter lows of –60ºF in Montana to summer highs of up to 120ºF in Nebraska, Kansas, and Missouri. The broad range in latitude, longitude, and elevation of the Missouri River basin and its location near the geographical center of the North American Continent results in a wide variation in climatic conditions, from season to season and from year to year. Because of these extreme variations in climatic conditions, extensive development of water resources has occurred.

Water Resources Development. Water resources development in the Missouri River basin has been dramatic over the past 150 years. Significant periods of development were prior to 1910 and since 1949. Early water resource developments were oriented largely towards single-purpose improvements to meet specific needs without substantial regard for other potential functions. However, as the region's demand for water resources grew, and technology improved, multi-purpose programs became more prevalent.

Numerous reservoirs and impoundments constructed by different interests for flood control, irrigation, power production, recreation, water supply, and fish and wildlife are located throughout the basin. Six mainstem dams constructed by the U.S. Army Corps of Engineers (USACE) are the most significant authorized flood control projects within the basin, providing a combined capacity in excess of 73.5 million acre-feet, of which more than 16 million acre-feet is for flood control. In addition to the six main stem projects operated by USACE, 65 tributary reservoirs operated by U.S. Bureau of Reclamation (USBR) and USACE provide over 15 million acre-feet of flood control storage. Irrigation first appeared in the Missouri Basin about 1650 by the Taos Indians along Ladder Creek in northern Scott County, Kansas. 'Modern' irrigation appeared in the basin in the late 1850s and early 1860s, and according to USBR estimates, irrigation and other depletions have now reached 13.5 million acre-feet annually above Rulo, Nebraska. The navigation channel and Federal levee system are authorized from the mouth upstream to Sioux City, Iowa, although no Federal levees have been constructed upstream of Omaha, Nebraska. There are numerous private levees along the river as well. The river is also extensively used for power-generating facilities, municipal water supplies and other uses.

Hydrologic Analysis

The hydrologic analysis performed for this study was composed of many steps. In order to provide a homogenous data set from which frequency analysis can be performed, effects of historic reservoir regulation and stream depletions had to be removed from the observed stream flow record. Depletions, mainly irrigation, were developed by the USBR (1999). This produced the data set referred to as the "unregulated flow" data set. A homogeneous "regulated flow" data set was then developed by extrapolating reservoir and stream depletions to current use level over the period of record. A relationship between the annual unregulated and regulated flow peaks was established in order to determine the regulated flow frequency at various points. A detailed description of methodology and data requirements may be found in USACE (2003) and Kay (2002).

Unregulated Flow. Unregulated flow can be defined as removing the effects of all consumptive uses of water (reservoir holdouts, irrigation, etc.) from the observed flow record; in other words the unregulated flow approximates the natural flow of the river. The unregulated flow data set was developed through use of the Unregulated Flow Development Model (UFDM), utilizing data sets for discharge, reservoir inflow and outflow or storage change, evaporation, precipitation, area-storage relationships, depletion data, and routing parameters, as well as observed flow at each gage.

Hydrologic Model Description (UFDM). Reliable runoff or flow data are a continuing need for purposes of efficient utilization of the available water supply in the Missouri Basin. With these data the nature and distribution of the supply becomes apparent, long term normals are defined more precisely, effects of basin water resources development can be estimated, and reservoir regulation effects on downstream flood flows or low water conditions may be developed. The UFDM is a computer model developed by the U.S. Army Corps of Engineers Reservoir Control Center at the Missouri River Region Office to determine unregulated flows for a base level of water resource development in the basin. The model is used to assist in determining flood control benefits for the mainstem reservoir system as well as to determine the amount of runoff from the upper Missouri River basin. A more detailed description of the UFDM modeling philosophy may be found in USACE (1973).

Once all input data were compiled, the model was run, covering the period of January 1, 1898 to December 31, 1997. Annual peaks and various other data were extracted from the output data.

Regulated Flow. Regulated flows are defined as those flows over a period of record, assuming a constant level of development; in other words the historic period is modeled as if all current reservoirs and irrigation depletions had been in place over the period of record. The regulated flow data set was developed through use of the Daily Routing Model (DRM), utilizing data sets for discharge, reservoir inflow and outflow, and depletions.

Hydrologic Model Description (DRM). The DRM was originally developed for use in the Missouri River Master Water Control Manual Update Study to evaluate flood control, interior drainage, and groundwater levels along the Missouri River and navigation contributions to the Mississippi River. The DRM contains 20 nodes including the six mainstem reservoirs and 14 gaging stations. The model utilizes two sets of input data. The first set of input files contains historic data in yearly files, and the second contains the various constants and variable parameters that define regulation decisions on the basis of flood control, navigation and other authorized purposes. Each yearly file contains 14 months of data – December of the previous year through January of the following year. More detailed information on the background and use of the DRM can be found in USACE (1998).

Input Data Development. Virtually all input data required for the DRM was previously developed for the unregulated flow analysis or developed for previous studies utilizing the DRM. Input data at gaging stations includes incremental reach inflow, observed gage flow data, and incremental reach depletion data. Input for the six mainstem reservoirs includes reservoir inflow, reservoir outflow, incremental reach inflow, evaporation, and storage. The remaining data sets are the rule curves that dictate the operation of the reservoirs given various parameters. The DRM uses depletion data by adjusting historic flows to present day consumptive water uses.

Frequency Analysis

A frequency analysis was performed on the unregulated flow data set at each gaging station. A relationship between regulated and unregulated peak annual flows was then developed at each station. The regulated-unregulated relationship was then used to derive the regulated flow frequency at each station.

Unregulated Flow Frequency. Frequency analysis was performed on peak annual unregulated flows at each gage, using Bulletin 17B procedures. Outliers were examined, and historical flood information was considered for increasing the reliability of estimates of less frequent floods. A mixed distribution was evaluated for applicability to the flow data. In order to obtain regionally consistent frequency profiles, skew values were regionalized for final frequency estimates.

Methodology. The Technical Advisory Group/Interagency Advisory Group (TAG/IAG) recommended using Bulletin 17B procedures after investigating various distribution methodologies and their applicability to the study area. Hence, analyses were performed on the annual peak unregulated flow series at each gage. However, it became apparent that this procedure did not adequately describe the upper end of the frequency curve for this portion of the Missouri River, based on the 1952 flood of record and on historical flood information prior to 1898. Further analyses would show that the snowmelt season and rainfall season events have different distributions, and should therefore be treated as a mixed population.

Mixed Population Analysis. Downstream of the Yellowstone River, the Missouri River has historically been subject to two main annual flood events - a spring plains snowmelt period, and a summer mountain snowmelt and plains rainfall period. Each series of floods was examined to see if they differed significantly and if the two flood periods could be combined to better describe the flow frequency at each gage. For purposes of analysis, the calendar year was divided into two seasons: spring (January 1 - April 30) and summer (May 1 - December 31). The majority of large floods above the Platte River result from plains snowmelt floods, while between the Platte and Kansas Rivers, plains snowmelt floods constitute the majority of top 5 floods.

USACE (1993) suggests the use of mixed population analysis when there are two or more different, but independent, causative conditions, as exists on the upper Missouri basin. The plains snowmelt and mountain snowmelt can be considered independent, or very nearly so, as plains snowpack typically peaks from February to early-April, and is almost non-existent by the end of April, while the mountain snowpack typically continues to accumulate until mid-May or later. Rainfall sometimes augments a plains snowmelt and sometimes a very late snowfall may occur in May over much of the upper basin. However, runoff characteristics differ greatly from early spring to late spring, with mostly frozen soil early in the spring resulting in much greater runoff than occurs later in the spring from the same volume of precipitation.

Regionalization of Statistics. In order to obtain regionally consistent frequency curves at each gage, it is necessary to regionalize the results of the flow frequency analysis. However, there is no guidance for regionalizing computed flow statistics in a mixed distribution, other than USACE (1993) stating, "*If annual flood peaks have been separated by causative factors, a generalized skew must be derived for each separate series to apply the log-Pearson Type III distribution as recommended by Bulletin 17B.*"

An examination of the station statistics shows a break in computed values of skew between Omaha and Nebraska City. Therefore, it was decided to regionalize skew for the gages above the Platte River and for those between the Platte and Kansas Rivers, and this was done by averaging the skew between stations in each reach. Use of the regional skew values results in the following frequency relationships at each gage (see Table 2).

Table 2. Regional Frequency Relations for Mixed Distribution, Yankton to Rulo, Unregulated Flow

Percent Chance Exceedance	Yankton	Sioux City	Decatur	Omaha	Nebraska City	Rulo
99	80500	83700	84000	86800	116700	115700
95	100100	103400	103700	107400	138700	138600
90	111800	115200	115600	119700	152000	152600
80	127600	130800	131100	136200	169800	171400
50	162200	165100	165300	172100	210100	214200
20	205300	207500	207400	216200	260900	268400
10	234600	236300	235300	245200	293900	303000
5	272100	273200	270100	280200	329100	340400
2	330300	330200	324400	334400	374100	386200
1	385600	383800	376000	386700	417600	429300
0.5	450000	446000	436100	447700	473600	485200
0.2	526400	519500	507100	519600	548700	557900

The regionally computed values show a slight decrease in discharge from Yankton to Decatur for the less frequent events. This can be attributed to the fact that the floodplain broadens tremendously downstream of Yankton and large flood waves are attenuated through this valley storage, and there is not much lateral inflow from Yankton to Omaha.

Regulated-Unregulated Relationships. Frequency analysis of a regulated data set should generally not be done by normal analytical methods. In order to determine an accurate regulated frequency relationship, it is necessary to determine the unregulated frequency relationship at the gage, and determine a relationship between regulated and unregulated peaks. The regulated-unregulated relationship is then applied to the unregulated frequency curve to determine the final regulated flow frequency relation.

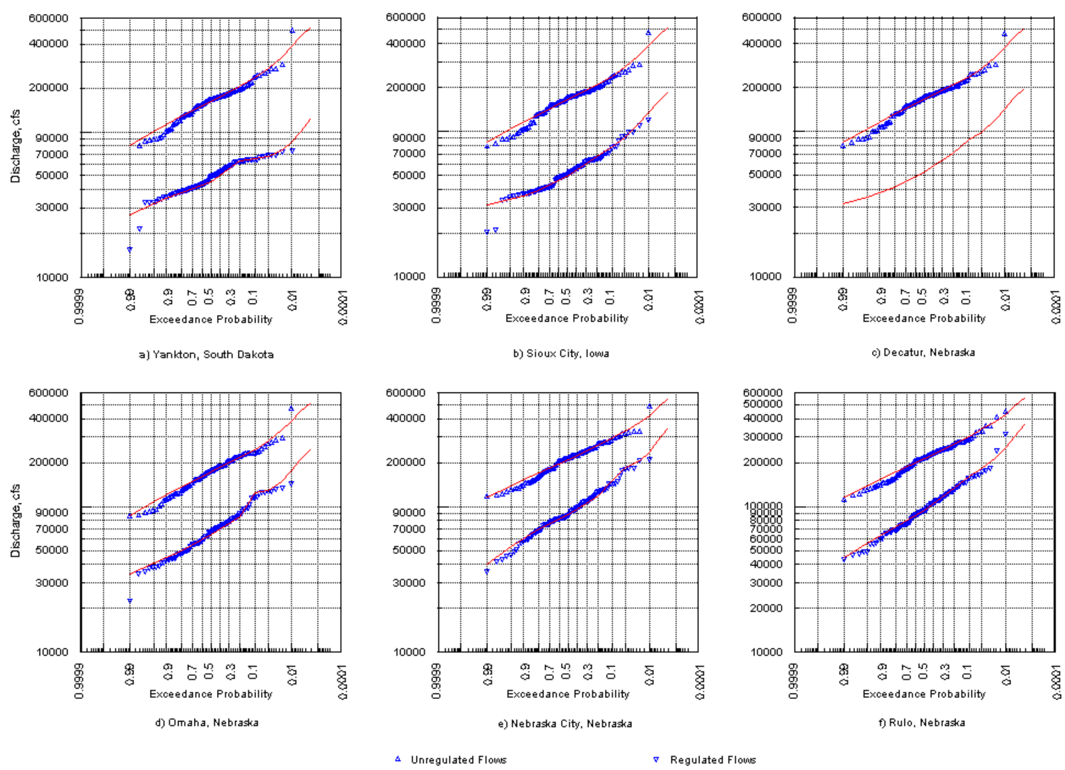
Methodology. The regulated-unregulated relationship is determined by pairing regulated and unregulated peak values with one another, and determining the relationship that best describes that pairing. Since the unregulated analysis relied upon a mixed distribution analysis, it was thought that perhaps the regulated-unregulated relationship could be derived by pairing the spring regulated and unregulated peaks and the summer regulated and unregulated peaks, determining the relationship for the spring and summer data, and combine the curves using the probability of union. However, this method proved unsatisfactory, as the spring and summer regulated values were not wholly independent, making the combination of the curves extremely cumbersome. Thus, it was decided to determine the regulated-unregulated relationship using annual peaks from the regulated and unregulated data sets. Data were first paired by year (year-ordered pairs), but this resulted in a great deal of scatter. Each data set was then ordered by magnitude of flood, and then paired (rank-ordered pair). This pairing resulted in a relationship that plotted through the median of the year-ordered pair data. In order to develop a regulated-unregulated relationship with a greater degree of confidence for the less frequent events, it was necessary to develop some "design" storms to synthesize data points to extrapolate the regulated-unregulated relationship. Several large floods that had roughly the same exceedance probability at 5 or more of the gages from Yankton to St. Joseph were chosen as representative in terms of timing as well as areal distribution. Those design floods that did not reasonably preserve the consistency of the volume-duration curve of the baseline flood were not used for extending the regulated-unregulated relationships. The remaining floods were then plotted with the year-ordered pairs and rank-ordered pairs to ensure they fell within the scatter of points. A 2^{nd}-degree polynomial was derived that best fit the upper half of the data points, and an ocular fit for each relationship was then determined over the entire range of data points.

Regulated Flow Frequency. In order to determine the final regulated flow frequency relationship at each gage, the regulated-unregulated relationship is applied to the unregulated frequency curves. This results in the regulated flow frequency relationships found in the table below. All values are relatively consistent with results of the previous study, with the exception of flows at Sioux City, where the 100-year flood value has increased by almost 50%.

Table 3. Regulated Frequency Curves, Yankton to Rulo

Percent Chance Exceedance	Yankton	Sioux City	Omaha	Nebraska City	Rulo
99	27000	31200	34600	40600	44900
95	32100	34000	40700	53500	55800
90	34800	36100	44800	60500	62800
80	38300	39100	49900	70500	72600
50	45200	49500	64100	88000	94800
20	63000	66800	85200	118500	132400
10	65000	78300	123500	149500	160600
5	68000	89900	129400	186000	181700
2	74700	113900	148000	206000	216800
1	84900	133700	174900	236500	252100
0.5	99400	157100	207700	278900	301200
0.2	123500	185400	248200	345400	370700

Plots comparing the unregulated and regulated flow frequency relationships are shown below (Figures 1a-f) for the gages from Yankton, South Dakota to Rulo, Nebraska. As can be seen, the effectiveness of flood protection afforded by the mainstem dams decreases as one moves downstream.



Figures 1a-f. Flow Frequency Relationships for Regulated and Unregulated Flow Conditions

Flow Regimes For Unregulated And Regulated Conditions

Daily flows from both the regulated and unregulated flow data sets were averaged over the period of record, and mean values of flow were derived for each day of the year. Additionally, upper and lower quartiles and deciles were derived from the data sets. The results show that for most years, the spring rise is relatively insignificant compared to the summer rise. The results also show that regulation has effectively removed both the spring and summer rises, and flows do not decline for several months later compared to the unregulated condition. Sample results are shown in Figure 2 for Sioux City and Nebraska City gages.

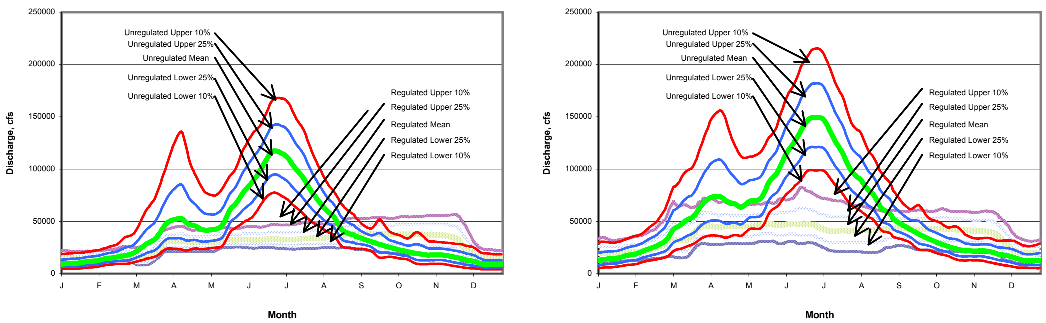


Figure 2. Upper and Lower Quartiles and Deciles and Mean Annual Regulated and Unregulated Flow, Sioux City and Nebraska City

Depletions have a significant impact on annual flow volume, but relatively little impact on flow frequencies. Since spring flows have a much greater impact on the upper portion of the frequency curves, and depletions are negligible in the spring, ignoring the impacts of depletions has only about a 1% impact on the computed 1% flood. However, depletions are important to consider, as they comprise slightly over 25% of the total mean annual natural flow from Yankton to Rulo, while losses of water through reservoir regulation, mainly through evaporation, account for nearly 10% of the mean annual natural flow at Sioux City.

The variability of flow over time is important to an understanding of the natural flow processes of a heavily regulated river. Richter, et al (1997) propose that 5 groups of hydrologic processes, further broken down into 31 hydrologic parameters, be used to evaluate how effectively a regulated river's flows match the pre-regulation flows. These 5 main groups include: magnitude of monthly water conditions, magnitude and duration of annual extreme water conditions, timing of annual extreme water conditions, frequency and duration of high/low pulses, and rate/frequency of water condition changes. As can be seen in Figure 2 above, monthly flow volumes during the primary high runoff months from March to August have been greatly reduced through reservoir regulation and flow volume decreases due to irrigation. Figure 3 below shows how drastically that reservoir regulation has changed the timing and magnitude of annual peak and minimum flows as well. It should be pointed out that the timing and magnitude of annual peaks shifts to the left and upwards for the regulated period as one moves downstream; however, the differences are still significant. The introduction of regulation on the river has also greatly reduced the frequency and duration of high flow pulses and significantly reduced the rate with which flow fluctuates as well as the frequency of fluctuations.

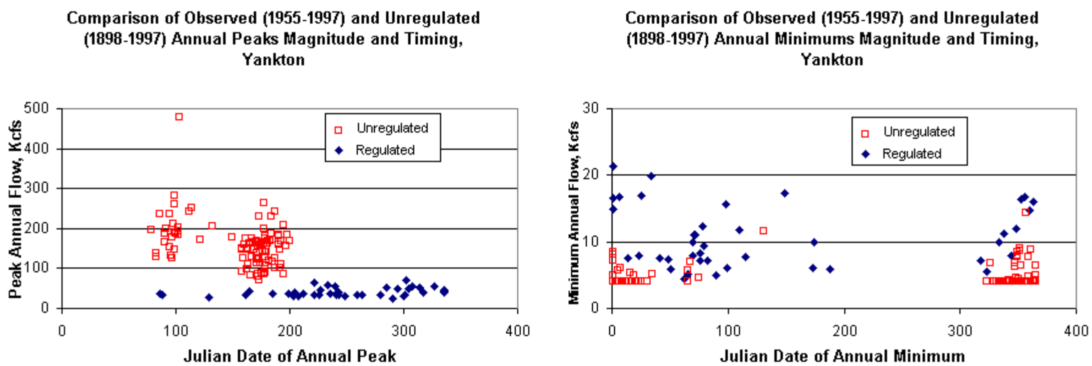


Figure 3. Comparison of Annual Peak and Minimum Flows Magnitude and Timing at Yankton for Unregulated Flows (1898-1997) and Observed Flows (1955-1997)

A complicating factor in comparing flow parameters over the period of record is that the middle third of the period of record has a significantly different flow regime than the first and last third. Even though this period contains the flood of record at every station in this reach and several other large floods (4 of the 5 largest at Yankton), this period also contains the majority of the driest years. On an annual basis, the period 1929-1966 had about 75-80% of the total flow volume as the rest of the period of record. It is interesting to note that for the months of April and June, the two months with the majority of peak annual flows, that monthly flow volumes from 1929-1966 were 85-95% of the rest of the period of record, but as flows dropped in other months, the 1929-1966 period fell to as low as 50% of the rest of the period of record, indicating that baseflows were substantially reduced during this period containing several extended droughts. Figure 4 below shows a comparison of mean monthly flow volumes for three periods within the period of record, with a * indicating those periods when monthly flow volumes are statistically significantly different from the last 30 years of record.

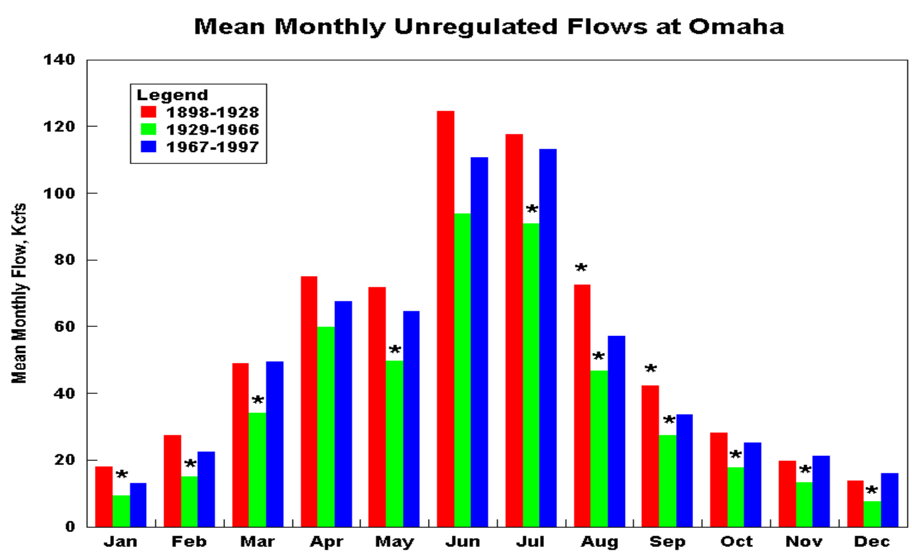


Figure 4. Comparison of Mean Monthly Flows for Various Periods

Conclusions

The frequency of flooding along the Missouri River has been greatly reduced by operation of the six Missouri River mainstem dams, although the effectiveness of regulation decreases as one moves downstream. The natural hydrograph of the Missouri River between the Yellowstone and Kansas Rivers is dominated by two main flood periods, spring and summer, that necessitate use of a mixed distribution analysis to compute flow frequencies for the unregulated condition. Flow frequencies for regulated conditions are best determined using a regulated-unregulated relationship applied to the unregulated flow frequencies. Accounting for all consumptive uses of water in the basin, including reservoir regulation and irrigation depletions, leads to a more homogeneous data set. Use of these data sets should lead to a better understanding of the relationship between the natural and current conditions flows on the Missouri River. The unregulated and regulated flow data sets will also be useful for other future studies of the Missouri River.

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